DURABILITY OF COMPOSITES IN AUTOMOTIVE STRUCTURAL APPLICATIONS

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In the summer of 1994, the U.S. Department of Energy initiated, in cooperation with the Automotive Materials Partnership of the United States Council for Automotive Research, a project at the Oak Ridge National Laboratory to address the durability aspects of polymeric composites for automotive structural applications. The purpose of this paper is to present the findings and observations developed to date and to outline future directions.

Objectives and Approach

The overall goal of the project is to develop experimentally-based, durability-driven design guidelines for automotive composite structures and to demonstrate their applicability to lightweight, manufacturable structures under representative field loading histories and environments. Key technical issues are the potentially degrading effects that (1) both cyclic and long-term sustained loadings, (2) various automotive environments, and (3) low-energy impacts can have on the dimensional stability, strength, and stiffness of automotive composite structures.

There are several candidate composite material systems for automotive structures, ultimately including carbon fiber systems. The approach has been to focus initially on just one of these — an isocyanurate reinforced with a continuous-strand, E-glass mat. The material is provided in the form of 1/8-in.-thick plaques. The following on-road conditions are being replicated on laboratory specimens from the plaques to generate data that will form the basis for a design guidelines framework:

- cyclic and sustained loadings,
- exposure to automotive fluids,
- temperature extremes,
- vibrations, and
- impacts from tool drops and roadway kick-ups of rocks.

Once guidelines are formulated for this reference material, less extensive testing will be required to adapt the guidelines to other material systems. The guidelines will be validated through subscale component tests.

In the following sections, results obtained to-date for the reference material are highlighted. Unless otherwise noted, the data presented are in ambient air, and they correspond to the weaker direction of the reference composite, which exhibits anisotrophy (about a 20% property variation in the plane of the plaques).

Reference Material Characterization and Modeling

Tensile behavior of the reference material is characterized by Figs. 1 and 2. Figure 1, which depicts tensile curves at various temperatures over the range (-40°F to 250°F) of automotive design interest, shows that at the upper end of the temperature range the strength and stiffness drop by about 30%. This is a short-coming of the preliminary reference material that is being improved. Figure 2 shows that, except for dynamic (high) rates of loading, the tensile properties are not very strain-rate dependent.

Creep response at various temperatures is illustrated in Fig. 3. After an initial primary response, the creep rate at room temperature, even for the relatively high stress of 15.5 ksi, is small. At 250°F, on the other hand, the rate is higher and the response is more ductile, even though the stress is lower.

Figure 4 conveys a key point. The plot shows the reduction in unloading modulus of elasticity relative to the loading modulus for specimens that were either (1) loaded in a tensile test to a prescribed percentage of the ultimate strength and then unloaded, or (2) loaded in a creep test to prescribed stress levels and allowed to creep for various times before unloading. The results show that for loadings below a certain threshold — say 20 to 35% of the ultimate tensile strength (UTS) — there is no loss of stiffness, and presumably no internal damage to the material. Above the threshold, damage develops and the stiffness decreases. The fact that the stress was sustained and creep occurred in the creep specimens appears not to have led to further degradation. The C-scan images at the top of Fig. 4 are of 1-in.-wide tensile specimens after having been loaded to the indicated stress levels. Little change is apparent below 40% of the UTS, while above 80% a distributed damage is apparent. Microstructural studies have indicated that this distributed damage, which often initiates at air bubbles, is primarily due to debonding at fiber-matrix interfaces and within fiber bundles.

This concept of distributed damage, manifested in stiffness degradation, as well as in permanent strains, has led to development of a damage-based viscoelastic model for predicting response of the reference composite. Comparisons of measured and predicted creep and recovery strains at three different creep stress levels are shown in Fig. 5. Note that the recovery portion of the tests was at zero stress.

Characterization and modeling results show that below the damage threshold, creep is linear with stress. Also, below the threshold creep strains are completely recoverable.

Effects of Cyclic and Long-Term Sustained Loadings

The basic fatigue response of the reference material, for a stress ratio of R = 0.1, is shown in Fig. 6 (the large amount of data generated at room temperature has been left off for clarity). At room temperature there is an endurance limit between 30 and 40% of the UTS (probably related to the threshold stress level previously discussed). At 250°F, the endurance limit is between 20 and 30% of the UTS. Above the endurance limit, damage increases with load cycles, and the stiffness, as an indicator of damage, decreases, as shown in Fig. 7.

Sustained loadings lead to creep rupture, again at stress levels above a threshold. The creep-rupture response is shown in Fig. 8, which reflects the results of many of the several hundred creep tests performed on the reference material. At temperatures up to 135°F, the data all fall in a band, represented by the top line in Fig. 8. Like in the tensile strength case, the creep strength of the reference material drops significantly at the higher temperatures (36% at 250°F and 10,000 h).

To determine the effect that prior creep strains have on residual tensile strength, groups of specimens were subjected to creep stresses of 13, 15, or 17 ksi and allowed to accumulate creep strains of 0.1, 0.2, or 0.3% (the average creep ductility at these stress levels is about 0.4%). The specimens were then tensile tested. The results are depicted in Fig. 9 (each point is the average of three test results). It can be seen that (1) prior creep strain accumulation has little effect on strength, and (2) there is likewise little effect on stiffness beyond the reduction produced by the initial loading.

Environmental Effects

Some eight different automotive fluids have been used in tests to determine their effects on tensile strength and stiffness, fatigue strength and stiffness, and creep strength. Key results are summarized in Fig. 10, where strength changes relative to ambient air test results are shown. In Fig. 10(a), groups of specimens were preexposed for 7540 h in the indicated fluids and then tensile tested in ambient air. The results in Fig. 10(b) come from fatigue curves obtained from specimens tested in the indicated fluids (all specimens were preconditioned in the fluid for 100 h prior to start of the test). The fatigue strengths at 10^6 cycles were compared to the corresponding strength from the room-temperature ambient air curve that was shown in Fig. 6. Likewise, the results in Fig. 10(c) came from creep-rupture curves obtained from creep tests in the indicated fluids. Strengths at 1000 h were compared to the corresponding ambient air value from the top curve in Fig. 8.

The results in Fig. 10 show that moisture, in its various forms, degrades tensile, fatigue, and creep strength, by up to 25% for the conditions shown. Petroleum-based fluids generally have little effect on the reference material. As expected, battery acid has a large degrading effect. Other automotive fluids generally are no worse than moisture in their effects.

More generally, fatigue endurance limits in the various fluids drop from the ambient air value of >30% of the UTS to the 20 to 30% of UTS range. Creep rates increase in the fluids, and the threshold stresses go down.

Besides fluids and temperature extremes, another possible environmental stressor for polymeric composites is small superimposed vibrations. Figure 11 shows creep rupture data for the reference material with and without a superimposed vibratory stress on the sustained creep load. The range of the vibratory load is about 270 psi (2% of the sustained failure stress at 10,000 h), and the frequency is 2000 cpm (similar to the frequency of an engine). This vibratory load reduces the 10,000 h strength by about 14%. So, this is another factor that must be taken into account, at least for the reference material, in developing safe design guidelines.

Effects of Low-Energy Impacts

To characterize the effects of low-energy impacts two special facilities were developed: (1) a pendulum that simulates tool drops (a relatively large mass at low velocities), and (2) an air gun that simulates road-way kickups (small masses at high velocities). In all cases, impact specimens were 1/8-in.-thick plates clamped on an 8-in.-diam. circle. The specimens were impacted at the center.

Baseline tests were run with a pendulum weight of 25.4 lb and an air-gun projectile weight of 0.05 lb. The impactor point was a 0.5-in.-diam. hemisphere in both cases. Results of these baseline tests are shown as the open circles in Fig. 12, which correlates the impact damage area, as determined from ultrasonic C-scans of the impacted specimens, with mass and velocity. The correlation shown — $\text{mass}^{0.564}$ x velocity — brings the pendulum and air-gun data together in a band that is represented by the single curve shown. Note that, again, there is a threshold.

The baseline curve in Fig. 12 was used to assess the effects of several key variables:

- impacts at -40°F,
- impactor diameters (0.25 in. and 4 in.),
- other air-gun impactor masses,
- specimen preexposure to distilled water for 1000 h, and
- battery acid exposure.

The solid points in Fig. 12 show a typical comparison — for results from the -40°F tests. The points consistently fall below the ambient air curve, indicating that impact resistance is slightly improved at -40°F. Other conclusions are:

- data for other impactor masses follow the same correlation,
- impactor diameter has little effect, and
- distilled water, and even battery acid, exposure does not increase the damage areas, which are very localized in all cases.

Baseline impact specimens were subsequently cut into 1-in.-wide specimens that were tensile tested to determine the effect of impacts on strength, stiffness, and elongation. Results are shown in Fig. 13 for a typical plate. Strength and stiffness are affected only in the immediate region of the damage area. The relative tensile strength at the center of each plate is shown in Fig. 14. With Figs. 12 and 14, residual strength can be predicted for a given impactor mass and velocity.

Future Directions

While the preliminary reference material has been reasonably well characterized and key technical issues have been addressed, at least in part, several important questions must still be explored in order to have a reasonably sound basis for developing and proposing design criteria. One important unresolved technical issue is whether or not a look at matrix dominated properties (e.g., shear, compression, and short beam test results) will change some of the conclusions discussed earlier in this paper. These conclusions are based largely on tests and loadings where the fiber properties dominate the material behavior, but real structures will also have stress states where matrix-dominated properties govern. Another issue is creep-fatigue — whether or not the synergistic effects of creep and fatigue occurring simultaneously are worse (or better) than the sum of the effects of the loadings acting alone. Resolving these issues, plus filling in minor data gaps, will be the focus of FY 1997 testing on the reference material. This effort will culminate with proposed design guidelines.

At the same time that work on the reference material is being completed, screening tests on a new material — the directed (chopped) fiber/urethane system being used for the Automotive Composite Consortium's (ACC) Focal Project 2 — will be identified and performed. These same screening tests can hopefully be applied to other potential material systems in the future and the results used to adapt the design guidelines developed for the reference material to the new materials.

Design guidelines will likely build on the threshold concepts mentioned throughout this paper. For those cases or areas of a structure where the resulting limits would be overly conservative and lead to unnecessarily thick sections, derating factors and damage accumulation rules will be developed and proposed.

To help properly focus the design guidelines development effort, a few scoping tests and analyses of a representative structural feature will be carried out. This structural feature will probably be a corrugated panel, which is currently being fabricated by ACC.